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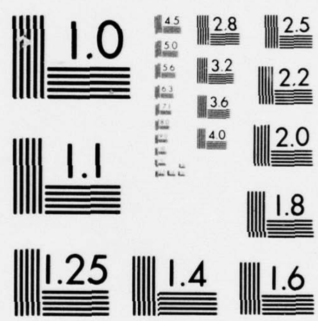

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ULTIMATE STRENGTH OF FIBER-REINFORCED CONCRETE UNDER CYCLIC FLEXURAL LOADING

by

Edward F. O'Neil

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Final Report

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ABSTRACT

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Cyclic flexural fatigue tests were conducted on 6- by 6- by 36-in. fiber-reinforced concrete beams containing 0.5-in. and 1.0-in. steel fibers to determine the change in ultimate flexural strength under fatigue loading. The beams were cycled at 3 Hz until failure occurred or 2 million cycles of load terminated the tests. The beams with 0.5-in. fibers produced a smaller change (45.22 percent) in ultimate flexural strength than the beams containing 1.0-in. fibers (49.68 percent). The method of failure of the beams was by a (Continued)

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20. ABSTRACT (continued).

gradual breakage of the bond between the steel and paste after the development of a crack in the concrete matrix, resulting in pullout of the fibers from the matrix.

ABSTRACT

PREFACE

Authority for this investigation was given by WESVB DF dated 17 August 1976, subject "In-House Laboratory Independent Research (ILIR). FY 7T and FY 77."

The steel fibers used in this program were obtained from the Steel Company of Canada and the United States Steel Company.

This report was prepared by Mr. E. F. O'Neil, Structures Branch, Engineering Mechanics Division (EMD), Concrete Laboratory (CL), U. S. Army Engineer Waterways Experiment Station (WES). Technical contributions in the planning of the study were provided by Dr. Tony Liu. The study was conducted under the general supervision of Mr. Bryant Mather, Chief, CL; Mr. John Scanlon, Chief, EMD; and Mr. James McDonald, Chief, Structures Branch.

The Commander and Director of the WES during the preparation and publication of this report was COL J. L. Cannon, CE. Mr. F. R. Brown was Technical Director.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	0.0254	metres
cubic feet	0.028317	cubic metres
cubic yards	0.76455	cubic metres
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (force)	4.448222	newtons
pounds (force) per square inch	0.006894757	megapascals

ULTIMATE STRENGTH OF FIBER-REINFORCED CONCRETE UNDER CYCLIC, FLEXURAL LOADING

INTRODUCTION

1. Fiber-reinforced concrete (FRC) has begun to gain acceptance as a useful form of structural concrete in the past 10 years. It is being used in an increasing number of applications where the presence of repetitive loads may present a problem of fatigue in the material. The nature of the material has lent itself to such applications as highway construction and repair, airfield pavements, bridge-deck overlays, and "armor plating" of jetties.

2. Repetitive loads below the static failure load of concrete tend to weaken the material and subsequently, after a number of cycles, cause failure under that fatigue loading. The number of cycles before failure increases with the decrease in the fatigue load. The ability of FRC to resist tensile loads is almost entirely dependent on the ability of the fibers to develop bond with the concrete matrix and distribute the stresses throughout the section. Much research has been done on the static strength of FRC, but few data are available concerning the effects of fatigue loading on the ultimate strength of the material.

Objective

3. The objective of this investigation was to determine the change in ultimate strength of fiber-reinforced concrete beams under cyclic loading, as compared to the ultimate strength of unfatigued beams, for specimens containing 0.5-in.* fibers and specimens containing 1.0-in. fibers, and to determine the method of failure of the fatigued beams.

Scope

4. The work included in this investigation involved fabrication and testing of five sets of fiber-reinforced concrete beams, analysis of the data collected and determination of the change in ultimate strength attributed to cyclic fatigue loading.

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 3.

PROPERTIES

Materials

5. The materials used to fabricate the beams and cylinders were taken from laboratory stock. The cement was a Type II portland cement designated RC-705. No admixtures were used in the concrete. The coarse and fine aggregates were crushed limestone. The specific gravity of the aggregates was 2.71 and the absorption of the coarse and fine aggregate was 0.40 and 0.60 percent, respectively.

6. The fibers used in the investigation were 0.01- by 0.02-in. in cross section and were cut from carbon steel sheet 0.01-in. in thickness. The ultimate strength of the fibers is approximately 50,000 psi, and the elongation in a 2-in. specimen length is 37-40 percent.

Mixtures

7. Three mixtures were used in the tests. The beams and cylinders containing steel fibers constituted mixtures 1 and 3. They differed only in the length of fibers used, with mixture 1 using 1.0-in. fibers and mixture 3 using 0.5-in. fibers. Mixture 2, the reference mixture, was essentially the same as the mixtures with fibers except that coarse aggregate was used to replace the volume occupied by the steel fibers. The mixture proportions for the three mixtures were as follows:

Mixture Proportions

	Mixtures Containing Fibers (cu ft/cu yd)	Reference Mixture (cu ft/cu yd)
Cement	4.01	4.01
Aggregate, Fine	9.69	9.69
Aggregate, Coarse	7.22	7.61
Fibers	0.39	0.00
Water	5.69	5.69

8. Each fiber mixture contained 2 percent fibers by volume of mortar, had an air content of about 2 percent, 1-3/4-in. slump and a unit weight of 153.8 lb/ft^3.

SPECIMEN FABRICATION

9. Five groups of specimens were cast from the three mixtures mentioned in paragraph 7. Two of the groups, designated A and B, were cast from mixture 1 containing 1.0-in. fibers. They were divided into two groups only because they were cast as two batches of the same mixture. Group C was the reference mixture that contained no fibers. It served as a reference for the data obtained from the mixtures containing steel fibers. Groups D and E were two batches cast from mixture 3 containing the 0.5-in. fibers.

10. Each group contained twelve 6- by 12-in. cylinders and five 6- by 6- by 36-in. beams. The cylinders were labeled according to group and numbered from 1 through 12. They were tested as follows:

Cylinders	Function
1-3	Compressive strength at 28 days
4-6	Splitting tensile strength at 28 days
7-9	Compressive strength at the start of cyclic fatigue of companion beams
10-12	Compressive strength at the completion of cyclic fatigue of companion beams

The beams in each group were also labeled according to group and numbered from 1 through 5. They were tested as follows:

Beams	Function
1	28-day static flexural strength
2	Static flexural strength at start of cyclic flexural testing to determine the ultimate flexural strength of the beams that were to be cycled
3-5	Three beams to be tested at various percentages of the ultimate flexural strength determined by testing beam 2 of the group

11. After the materials were weighed out, they were combined in a 7-1/2 cu ft revolving-drum mixer with the fibers being added a handful at a time to ensure good distribution throughout the mixture. The beam

and cylinder molds were filled and the concrete consolidated by means of electric vibrators inserted into the mixture. The specimens were then covered with plastic sheet to prevent moisture loss. After 24 hours they were stripped from their molds. After 28 days of moist curing following stripping they were stored in laboratory air until they were tested. Each group of beams and cylinders was cast and tested on monthly intervals in order to ensure that the cyclic flexure tests could be conducted when the beams were approximately the same age.

TESTING PROCEDURE

Static tests

12. At 28 days age cylinders 1-3 of each group were capped and tested in unconfined compression according to CRD-C 14-73[1] to determine the 28-day compressive strength. At the same time cylinders 4-6 were tested according to CRD-C 77-72[1] to determine splitting tensile strength. Also at 28 days age beam 1 of each group was tested in third-point flexure to determine the static flexural strength of the beam.

13. At approximately 90 days age the cyclic flexure tests were begun. At the initiation of cyclic testing, cylinders 7-9 of each group were tested in unconfined compression to determine the compressive strength at the beginning of cyclic loading, and beam 2 was tested in third-point static flexure to determine the ultimate flexural load. This beam ultimate load was then used to determine the percentage of ultimate flexural load at which beams 3, 4, and 5 of each group would be cycled.

Cyclic tests

14. The test setup for the cyclic flexural tests is shown in Figure 1. The beams were tested in third-point flexural loading in a nonreversal type of loading from zero load to a predetermined percentage of the ultimate static flexural load determined by testing beam 2, and then back to zero. The cyclic testing apparatus consisted of a 50,000 lbf closed loop hydraulic actuator controlled by a sine function generator. The actuator was held in a 300,000 lbf capacity test frame. Since the loading configuration was nonreversal loading, the beams had to be

statically loaded to 50 percent of their final percentage of ultimate on the first cycle and then cycled about that median value. They were cycled at a loading rate of 3 Hz until they were failed or until they reached two million cycles. The load on the specimens was recorded on light-sensitive paper fed through a recording oscillograph and the number of cycles to failure was recorded on a universal counter with a recording capacity of ten million cycles.

Figure 1. Cyclic fatigue testing apparatus

RESULTS AND DISCUSSION

Static test results

15. The compressive strength and tensile splitting strength histories of cylinders shown in Table 1 indicate that the compressive strength of the fiber-reinforced concrete is approximately the same regardless of length of fiber in the mixture, and the tensile strength improves with the length of the fiber. The results reported by various researchers on the effect of fibers on the compressive strength of fiber-reinforced concrete show some difference in findings. Williamson[2] found

increases in compressive strength of up to 23 percent over compressive strengths of 6- by 12-in. concrete cylinders without fibers, while the results found by Kar and Pal[3] and those of Chen and Carson[4] show that there is little if any increase in compressive strength due to addition of steel fibers. The results given here show a small increase in compressive strength over the results for the control mixture, but the specimens with the 0.5-in. fibers (aspect ratio of 30*) and the specimens with the 1.0-in. fibers (aspect ratio of 60) had approximately the same compressive strengths at 28 days, at the beginning of cyclic testing, and at the completion of cyclic testing (Table 2).

16. The tensile-strength data of Table 1 indicate that the strength increases with the increase in length of fiber or increase in aspect ratio. These results generally agree with the results of others on the tensile strength of FRC. Naaman et al[5] as well as Johnston and Coleman[6] showed strength increases with increase in aspect ratio. Their results were taken from direct tensile tests while the present investigation uses indirect tensile tests, but the agreement in strength increase with aspect ratio increase is also apparent here. Regardless of method of test, the tensile strength after failure of the matrix is a function of the length, quantity, and orientation of the fibers. Consequently the length and orientation of the fiber will affect the bond and pullout resistance indicating that the tensile strength should increase as the aspect ratio increases.

17. Table 2 shows the change in compressive strength of the companion cylinders during the course of cyclic loading. The table indicates that there was a small increase in compressive strength of the groups over the period of cyclic loading. The decrease in strength of the control mixture from 93 to 107 days cannot be explained other than through the chance occurrence of three low cylinder breaks, otherwise the change in compressive strength from beginning to end of cyclic testing indicated a small increase in strength.

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* Aspect ratio is the ratio of the length divided by the equivalent diameter.

18. The compressive strengths of the cylinders in group E between 90 and 125 days are smaller in magnitude than those of A through D, while the 28-day compressive strength is about the same as the rest of the groups. Since all groups were moist cured until 28 days, the group E specimens began to lose strength subsequent to 28 days and experienced a lower rate of hydration due to greater specimen drying in the laboratory from 28 days through 125 days.

Modulus of rupture

19. The data presented in Table 3 show the relationship between the modulus of rupture and the aspect ratio of the fibers used in the investigation. The data show that there is only a slight difference between the average value for groups A and B, the beams containing fibers with aspect ratio of 60 (1-in. fibers); and groups D and E, the beams containing fibers with aspect ratio of 30 (0.5-in. fibers). The higher average is in the 1.0-in. fiber beams. Much of the data collected to date on the modulus of rupture has indicated that the modulus of rupture increases with increasing aspect ratio.[7,8,9] This is similar to the relationship between tensile strength of FRC and aspect ratio, and since the modulus of rupture is essentially a tensile test, it would support it for the same reasons.

Cyclic test results

20. The beams of each group that were subjected to cyclic loading were loaded in a nonreversal loading mode. They were loaded statically to one-half of their cyclic load on the first cycle and then cycled from there through the maximum cyclic load and back to zero load until either failure or two-million cycles of loading occurred. This nonreversal mode of loading was selected to simulate the conditions that would be encountered in a bridge deck or airfield pavement under repetitive traffic loading where the FRC would be subjected to a stress under direct load and then a small rebound stress of opposite sine upon removal of the load.

21. Conventionally, the method of reporting cyclic fatigue testing results is by a semi-logarithmic plot of load versus number of cycles to failure. Table 4 and Figure 2 show the relationship between the percentage of ultimate static load applied to the specimen and the number of

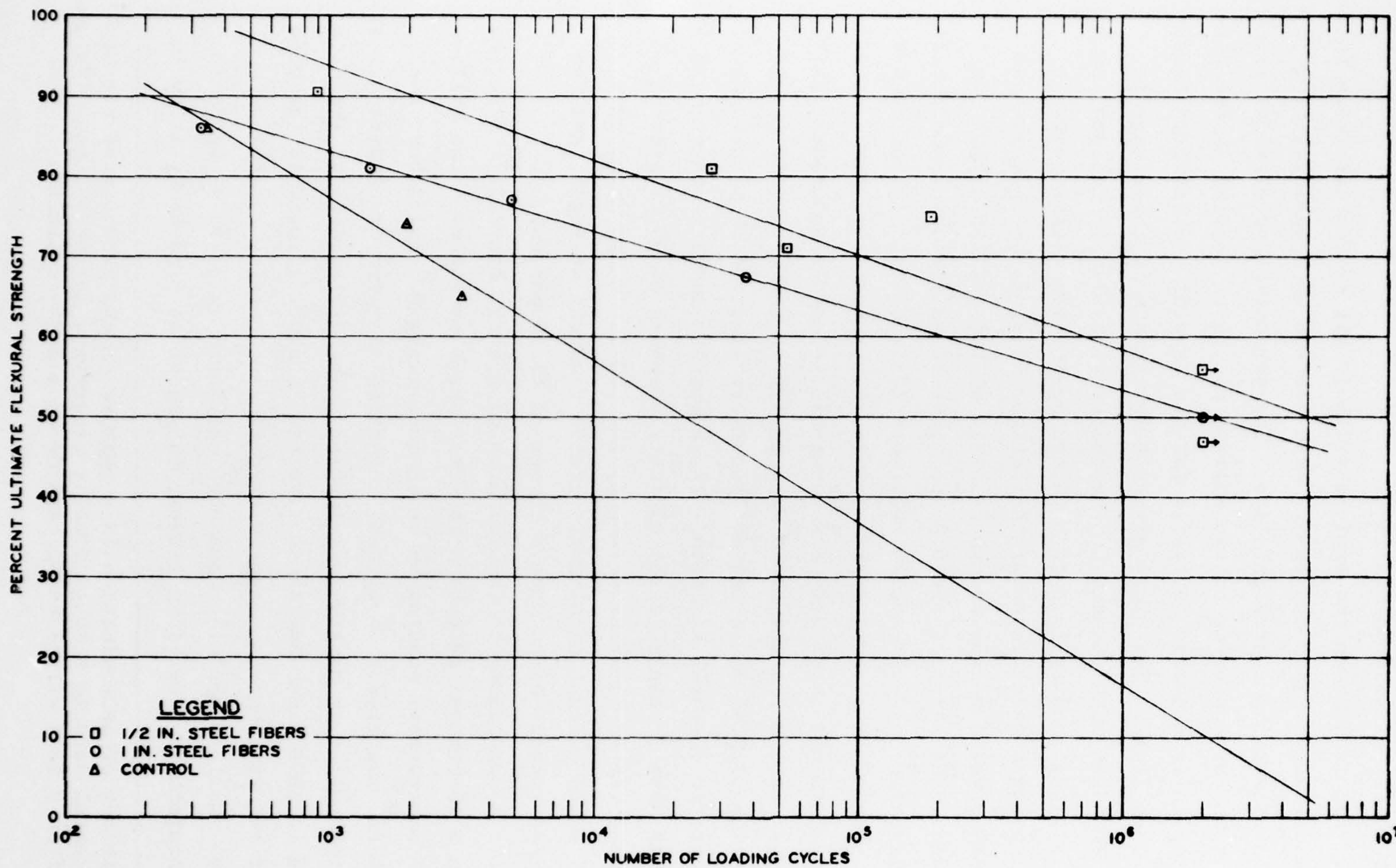

Figure 2. Semi-logarithmic plot of load versus number of cycles to failure

cycles at that load to cause failure.

22. Figure 2 shows the semi-logarithmic fit of the data made for the three different types of beams. When plotted on a semi-logarithmic graph this appears as a straight line. The percentage of ultimate flexural strength corresponding to two million cycles of loading is the percentage typically reported in cyclic fatigue studies and referred to as the endurance limit. The plots give a relationship of the change in ultimate strength with respect to the number of cycles to failure, such that for a given loading that is a percentage of the ultimate static flexural strength an estimate of the fatigue life of the specimen can be made and a value of the endurance limit at two million cycles can be provided. The tests of the 0.5-in. fiber beams yielded a coefficient of determination* of 0.87 and an endurance limit at two million cycles of 54.78 percent, the tests of the 1.0-in. fiber beams yielded a coefficient of determination of 0.99 and a two-million-cycle endurance limit of 50.32 percent, while the beams with no fibers had a coefficient of determination of 0.95 and a two-million-cycle limit of 10.61 percent of ultimate static flexural strength. These results indicate that the 0.5-in. fiber beams have a change in the ultimate strength of 45.22 percent of the ultimate static flexural strength, the 1.0-in. fiber beams have a change of 49.68 percent of ultimate static flexural strength, and the unreinforced control beams have a change of 89.39 percent.

23. In comparison to the research of others, Romauldi[10] reported less than a 10-percent reduction in first crack strength at two million cycles of nonreversal loading on beams containing 0.5-in. fibers and Batson et al[9] reported a 26-percent reduction in first crack strength at two million cycles in nonreversal loading. The differences in the data collected in this paper and those referred to above illustrate the wide spread of results that can occur with different testing conditions and variables. While Romauldi's data were collected on 3- by 6- by 36-in. beams containing 0.5-in.-long fibers, Batson et al used 4- by 6- by 102-in.

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* Coefficient of determination is a measure of the goodness of fit of experimental data to a statistically determined set of values. (Values range from 0 to 1 with 1 being considered a perfect fit.)

beams containing 0.5-in.-long by 0.0066-in.-diameter fibers and 1.25-in.-long by 0.014-in.-diameter fibers and both reversal and nonreversal loading modes. The results presented here are lower than those given by both authors above. Part of the explanation of the lower values lies in the method of reporting the data. Since more energy is required to fail a beam in flexure than to produce the first crack, a percentage reduction in ultimate strength due to cyclic loading would be greater than a percentage reduction in first crack strength. Although the mechanisms involved in fracture to failure of fiber-reinforced concrete are more involved than first crack strengths, it was felt that the results would be more useful from a practical standpoint if compared to ultimate flexural strength since this parameter is generally accepted as a strength acceptance criteria.

24. The results presented for the control are unreliable due to the small number of specimens tested. Values were reported at 86, 74, and 65 percent ultimate. These values when projected to two million cycles produced a change in strength of 89 percent. Several researchers[10,11] have established the endurance limit of unreinforced concrete beams to be between 50 and 55 percent of the ultimate flexural strength of a statically failed beam. This indicates that for unreinforced concrete the relationship between load and number of cycles of load to failure will level off at about 50 percent of ultimate strength. It is not known whether this is true for FRC. All the data collected in this study at percentages of ultimate flexural load below 65 percent were runout tests terminated at two million cycles of loading. Their graphs could very possibly exhibit behavior similar to nonreinforced concrete beams only with the endurance limit at a higher percentage of ultimate strength than for the nonreinforced case due to the greater stress distribution and crack-arresting mechanisms of the fiber reinforcement. The values of endurance limit given here were calculated with the runout data interpreted as failures at two million cycles because no appropriate number of cycles greater than this number could be assumed.

25. All the flexural beams whether tested statically or cyclically failed by pullout of the fibers. Figure 3 shows the broken face of a

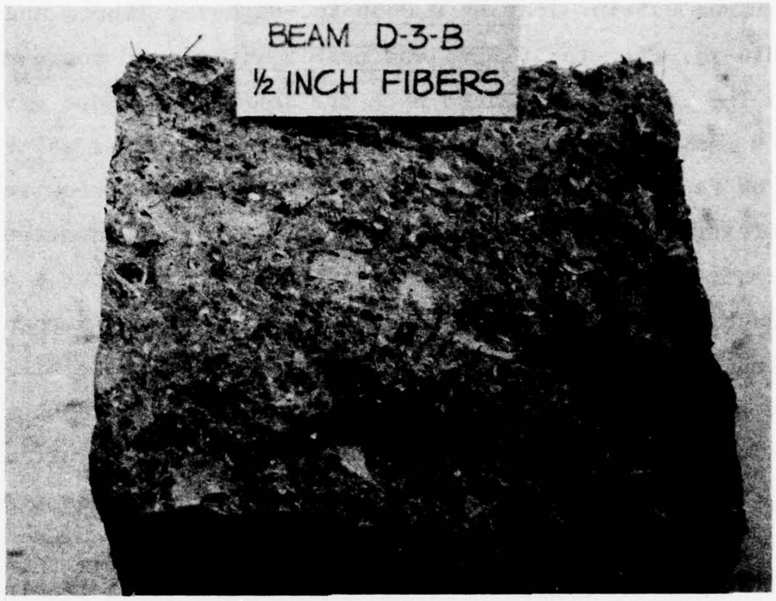

Figure 3. Typical cross section of 0.5-in. fiber beams showing pullout of fibers.

typical beam. Although difficult to distinguish in a black and white photograph, the mechanism of failure was loss of bond between cement paste and fiber. Steel fibers used in concrete act as crack arrestors. As a crack develops in a concrete specimen, it will propagate along its path of least resistance until it encounters a fiber or other crack arrestor that crosses its direction of travel. At this point the stress in the concrete at the crack tip is transferred to the crack arrestor. As the loading increases, or, in the case of cyclic loading, is continued either the fiber (crack arrestor) will pull out due to insufficient bond or break if the bond strength exceeds the tensile strength of the arrestor; the repetitive load caused bond breakage at each cycle such that the final failure mode was pullout of the fiber.

Postfatigue static flexural strength

26. All beams that survived two million cycles of loading were loaded statically to failure. Column 5 of Table 4 gives the modulus of rupture for the three tests that reached two million cycles. The modulus of rupture obtained subsequent to two million cycles of load on the

group B and group E beams was larger than their prefatigue counterpart. This phenomenon has been reported by both Romauldi[10] and Batson[9] in their postfatigue flexural strength tests. Romauldi explained that as the FRC hardens, tensile stresses are set up in the matrix due to restriction of shrinkage by the fibers. He theorized that the fatigue loading produced an accelerated creep of the beam, thereby reducing the tensile stresses in the matrix caused by restricted shrinkage and allowing additional loading prior to failure to match the reduction of tensile stress achieved by cyclic fatigue. No attempt is made here to improve on this theory since it was supported by the data gathered here.

CONCLUSIONS

27. From the testing conducted in this investigation it is concluded that at two million cycles of nonreversal loading on concrete beams containing 0.5-in. fibers and 1.0-in. fibers, the beams with 0.5-in. fibers produced a smaller change in ultimate flexural strength of 45.22 percent than the beams containing 1.0-in. fibers which experienced 49.68 percent change. It is also concluded that the results reported for the control beam are in error due to the small number of samples tested.

28. The method of failure of the beams was by a gradual breakage of the bond between the steel and paste after the development of a crack in the concrete matrix, resulting in pullout of the fibers from the matrix.

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<u>Table 1</u>

<u>Compressive and Tensile Strengths of Cylinders</u>

<u>at 28 Days Age (psi)</u>

Specimen No.	Compressive Strength, psi	Average psi	Remarks
A-1	5630		
A-2	5610	5627	Group A = 1-in. fibers
A-3	5640		
B-1	5440		
B-2	5220	5470	Group B = 1-in. fibers
B-3	5750		
C-1	5320		
C-2	5640	5400	Group C = no fibers
C-3	5240		
D-1	5520		
D-2	5370	5553	Group D = 1/2-in. fibers
D-3	5720		
E-1	5610		
E-2	5510	5563	Group E = 1/2-in. fibers
E-3	5570		

Specimen No.	Tensile Strength, psi	Average psi	Remarks
A-4	750		
A-5	705	732	Group A = 1-in. fibers
A-6	740		
B-4	805		
B-5	745	780	Group B = 1-in. fibers
B-6	790		
C-4	555		
C-5	560	550	Group C = no fibers
C-6	535		
D-4	625		
D-5	625	632	Group D = 1/2-in. fibers
D-6	640		
E-4	640		
E-5	640	635	Group E = 1/2-in. fibers
E-6	625		

Table 2

Compressive Strength of Cylinders During Cyclic Testing

Specimen No.	Compressive Strength, psi	Average psi	Age, days	Remarks
A-7	7550			
A-8	7460	7520	91	Beginning of group A cyclic tests
A-9	7550			
A-10	7930			
A-11	7550	7810	111	End of group A cyclic tests
A-12	7950			
B-7	*			
B-8	*	--	--	Beginning of group B cyclic tests
B-9	*			
B-10	7680			
B-11	7820	7737	127	End of group B cyclic tests
B-12	7710			
C-7	5790†			
C-8	7640	7515	93	Beginning of group C cyclic tests
C-9	7390			
C-10	6950			
C-11	6890	6933	107	End of group C cyclic tests
C-12	6980			
D-7	7460			
D-8	7710	7550	108	Beginning of group D cyclic tests
D-9	7480			
D-10	7360			
D-11	7800	7567	113	End of group D cyclic tests
D-12	7540			
E-7	6130			
E-8	6570	6500	92	Beginning of group E cyclic tests
E-9	6800			
E-10	6790			
E-11	6900	6860	125	End of group E cyclic tests
E-12	6880			

* Compressive tests not made at initiation of cyclic testing.

† This data eliminated from average as low test.

Table 3

Modulus of Rupture of Beams Tested in Static Flexural Loading

Beam No.	Modulus of Rupture, psi	Age, days	Remarks
A-1-B	748.6	28	1-in. fibers
A-2-B	797.5	108	1-in. fibers
B-1-B	687.5	28	1-in. fibers
B-2-B	580.5	92	1-in. fibers
C-1-B*			
C-2-B	492.7	90	No fibers
D-1-B	648.2	28	0.5-in. fibers
D-2-B	565.4	118	0.5-in. fibers
E-1-B	683.7	28	0.5-in. fibers
E-2-B	717.0	92	0.5-in. fibers

* 28-day modulus of rupture test not made on control beam.

Table 4

Cyclic Flexural Fatigue Data For Control, 1-in. and 0.5-in. Fiber Beams

Beam No.	Cyclic Load, lbf	Percent Ultimate Static Load	No. Cyc to Failure	Modulus of Rupture, psi	Remarks
A-3-B	4470	86	324	--	1-in.
A-4-B	4000	77	4,810	--	1-in.
A-5-B	3520	67	37,217	--	1-in.
B-3-B	3160	83	1,461	--	1-in.
B-4-B	1900	50	2,000,000†	980.1	1-in.
B-5-B	Test destroyed during power failure			--	1-in.
C-3-B	2800	86	342	--	Control
C-4-B	2400	74	1,950	--	Control
C-5-B	2100	65	3,168	--	Control
D-3-B	2770	75	187,184	--	1/2-in.
D-4-B	3350	90	884	--	1/2-in.
D-5-B	2990	81	27,952	--	1/2-in.
E-3-B	2200	47	2,000,000†	688.3	1/2-in.
E-4-B	2650	56	2,000,000†	797.5	1/2-in.
E-5-B	3350	71	53,790	--	1/2-in.

† Runout test stopped at 2,000,000 cycles.

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

O'Neil, Edward F
Ultimate strength of fiber-reinforced concrete under cyclic, flexural loading / by Edward F. O'Neil. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1978.
16, [4] p. : ill. ; 27 cm. (Miscellaneous paper - U. S. Army Engineer Waterways Experiment Station ; C-78-5)
Prepared for Assistant Secretary of the Army (R&D), Department of the Army, Washington, D. C., under Project No. 4A161101A91D.
References: p. 16.

1. Concrete beams. 2. Cyclic flexural loading. 3. Endurance limit. 4. Fatigue strength. 5. Fiber-reinforced concrete. 6. Pullout resistance. 7. Ultimate flexural strength. I. United States. Assistant Secretary of the Army (Research and Development). II. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Miscellaneous paper ; C-78-5.
TA7.W34m no.C-78-5